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WEATHER AND WHEAT YIELDS at LINCOLN COLLEGE, NEW ZEALAND.

by DR. E. KIDSON,
DIRECTOR OF METEOROLOGICAL SERVICES, NEW ZEALAND.

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The accompanying paper by Dr. Kidson has been presented to the Conference by New Zealand, as a contribution to the discussion on the use of meteorological data in the improvement of crop estimates.

The paper is being printed in the Science Journal of New Zealand.

WEATHER AND WHEAT-YIELDS AT LINCOLN COLLEGE, NEW ZEALAND.

By Dr. E. Kidson, Director of Meteorological Services.

At the beginning of the present year it was decided to undertake an investigation of the relationship between the various meteorological factors and the wheat-yield at the Canterbury Agricultural College, Lincoln.

In order to carry out such an investigation satisfactorily one requires a homogeneous set of records of wheat-yield covering a very long period. The yields should be unaffected by changes in methods of cultivation, manuring, seed varieties, or other extraneous influences. Should such changes have intervened, the yields should be corrected for their effects and so reduced to a uniform standard. Complete and homogeneous meteorological records for the corresponding period are, of course, equally essential. Unfortunately, there are numerous breaks in the meteorological record, and the growth of trees had, by 1927, very seriously affected the site of the meteorological station. Wind and sunshine would be the two elements most affected, but it is probable that there were smaller influences on temperature and rainfall.

TABLE I. - WHEAT-YIELDS AT LINCOLN COLLEGE.

Year.	Acres.	Yield per Acre.	Correction.	Corrected Yield per Acre.	Departure from Average
		Bushels	Bushels.	Bushels.	Bushels.
1883	..	42.0	+ 8	50.0	+ 8
1884	..	32.0	+ 8	40.0	- 2
1885	..	41.0	+ 8	49.0	+ 7
1886	..	30.0	+ 8	38.0	- 4
1887	..	25.0	+ 8	33.0	- 9
1899	..	47.0	+ 8	55.0	+13
1907	..	37.0	0	37.0	- 5
1909	125	57.1	0	57.1	+15
1910	111	41.0	0	41.0	- 1
1911	..	38.5	0	38.5	- 3
1912	..	51.0	0	51.0	+ 9
1913	..	44.0	0	44.0	+ 2
1914	..	50.0	0	50.0	+ 8
1915	..	51.0	0	51.0	+ 9
1916	113	24.3	- 1	23.3	-18
1917	..	29.3	- 1	28.3	-13
1918	170	28.0	- 1	27.0	-15
1919	120	50.0	- 1	49.0	+ 7
1920	133	33.2	- 1	32.2	- 9
1921	90	38.0	- 1	37.0	- 5
1922	121	49.0	- 2	47.0	+ 5
1923	127	54.2	- 3	51.2	+ 9
1924	105	48.0	- 4	44.0	+ 2
1925	89	43.0	- 5	38.0	- 4
1926	87	42.5	- 6	36.5	- 6
1927	89	47.7	- 7	40.7	- 1
1928	101	51.5	- 7	44.5	+ 3

WEATHER AND WHEAT-YIELDS AT LINCOLN COLLEGE, NEW ZEALAND.

By W. S. Wilson, Director of Meteorological Services.

At the beginning of the present year it was decided to undertake an investigation of the relationship between the various meteorological factors and the wheat-yields at the Canterbury Agricultural College, Lincoln.

In order to carry out such an investigation satisfactorily one requires a homogeneous set of records of wheat-yields covering a very long period. The yields should be uniformly obtained by obtaining an ordinary maximum, maximum seed variety, or other extraneous influences. Hence the yield-effects need be reduced to a uniform standard. Complete and homogeneous meteorological records for the corresponding period are, of course, equally essential. Unfortunately, there are numerous breaks in the meteorological record. For the growth of crops and, by inference, very seriously affected the site of the meteorological station. Wind and rainfall would be the two elements most affected. But it is probable that there were secular influences on temperature and rainfall.

TABLE I. — WHEAT-YIELDS AT LINCOLN COLLEGE.

Year.	Acres.	Yield per Acre.	Correction.	Corrected Deviation from Mean Yield per Acre.
1908	..	42.0	+ 6	- 8
1909	..	52.0	+ 8	- 2
1910	..	41.0	+ 8	+ 9
1911	..	50.0	+ 8	- 4
1912	..	38.0	+ 8	- 9
1913	..	47.0	+ 8	+12
1914	..	37.0	0	- 8
1915	150	37.1	0	+10
1916	171	41.0	0	- 1
1917	..	30.5	0	- 3
1918	..	31.0	0	+ 2
1919	..	44.0	0	+ 3
1920	..	30.0	0	- 2
1921	..	32.0	0	+ 3
1922	113	24.3	- 1	-10
1923	..	30.2	- 1	-13
1924	170	25.0	- 1	-17
1925	150	30.0	- 1	+ 7
1926	150	..	- 1	- 3
1927	..	36.0	- 1	- 6
1928	113	33.0	- 2	+ 6
1929	150	34.0	- 2	+ 6
1930	160	44.0	- 2	+ 3
1931	..	43.0	- 3	+ 4
1932	..	43.0	- 3	- 4
1933	..	37.7	- 3	- 3
1934	101	41.0	- 3	- 1

The available data regarding wheat-yields were furnished by Dr. Hilgendorf, and are given in the first three columns of Table I. The figures were accompanied by the following remarks:-

"This set of figures is, we think, quite homogeneous in that all the yields are off the same 400 acres of wheat-land, and in that each year represents the average of five or six crops. The varieties have certainly changed, but this has been done so slowly that no particular date can be pointed out as being that on which the new varieties were introduced; but a gradual introduction of improved strains started around the year 1918. Cultural methods, and especially the use of manures, have also changed, but this also has been gradual; and the turning-point, if any date can be mentioned as a point, occurred during the hiatus in our records, before 1899. The two following years are deserving of note - viz. the harvest of 1918 was reduced by an epidemic of rust, occurring in December 1917, and the harvest of 1920 was reduced by a frost of about 10 or 11 degrees on the 9th or 11th December, 1919."

It was found that the years 1883-87 and 1899 gave an average yield 8 bushels lower than the mean for all years. This was assumed to be due to the lack of efficiency in methods of production in the early as compared with the later years. The effect of improved methods was regarded as constant for the years 1907 to 1915 inclusive. From 1916 onwards it was assumed that the improvements were responsible for a progressively increasing additional yield. The corrections given in the fourth column of Table I were therefore arrived at. The annual yields were therefore corrected by these amounts. The resulting yields are assumed to have been reduced to a uniform standard and to be directly intercomparable. The method was obviously crude, but it was at least unbiased, and the corrections once having been estimated they were left unchanged. It would not be possible to do much better. We arrive, then, at the annual departures from the average yield given in the last column of Table I. Subsequent calculations indicated that the corrections used for the last four years were not very satisfactory.

The next procedure was to find the direct correlation between the various meteorological elements and the wheat-yield. This was done by taking the monthly values of the meteorological elements and correlating, at first, for each month separately. Some of the results obtained are given in Table II. It was assumed that the yield in each year might be affected by the meteorological conditions obtaining between the beginning of March in the previous year to the end of February in the year in question.

TABLE II. CORRELATIONS WITH WHEAT-YIELDS AT LINCOLN COLLEGE.

Month.	Element.				
	Rainfall.	Maximum Temperature.	Minimum Temperature.	Number of Frosts.	Number of West and North-west Winds at 9 a.m.
January	+ .30	-.26	+ .09	..	-.39
February	-.50	-.14	+ .17	..	-.11
March	-.07	+ .03	-.03	..	-.27
April	-.13	-.12	+ .02	- .01	+ .26
May	-.41	-.07	-.14	+ .10	+ .06
June	.00	+ .04	-.07	- .20	+ .16
July	+ .27	-.29	-.20	+ .16	+ .06
August	-.26	+ .08	-.12	+ .05	+ .11
September	-.17	.00	.00	+ .15	+ .37
October	+ .07	-.24	-.25	+ .07	-.33
November	+ .44	-.05	-.27	-.28	-.20
December	+ .37	-.35	+ .08	-.09	-.44

The available data regarding wheat-yields were furnished by Dr. Hjelmquist, and are given in the first three columns of Table I. The figures were accompanied by the following remarks:-

"This set of figures is, we think, quite homogeneous in that all the yields are all the same ACC acres of wheat-land, and in that each year represents the average of five or six crops. The varieties have certainly changed, but this has been done so slowly that no particular date can be pointed out as being that on which the new varieties were introduced; but a gradual change-not without improved strains started around the year 1890. Cultural methods, and especially the use of manures, have also changed, but only also has been gradual; and the turning-point, if any date can be mentioned as a point, occurred during the blights in our records, before 1898. The two following years are deserving of note - viz. the harvest of 1910 was reduced by an epidemic of rust, occurring in October 1917, and the harvest of 1920 was reduced by a frost of about 10 or 11 degrees on the 9th or 11th December, 1919."

It was found that the years 1893-97 and 1899 gave an average yield 8 bushels lower than the mean for all years. This was assumed to be due to the lack of efficiency in methods of cultivation in the early as compared with the later years. The effect of improved methods was regarded as constant for the years 1897 to 1914 inclusive. From 1918 onwards it was assumed that the improvements were responsible for a progressively increasing additional yield. The corrections given in the fourth column of Table I were therefore applied at. The annual yields were thereby corrected by these amounts. The resulting yields are assumed to have been reduced to a uniform standard and to be climatically intercomparable. The method was obviously crude, but it was at least obligated, and the corrections once having been estimated they were left unchanged. It would not be possible to do much better. We arrive, then, at the annual departures from the average yield given in the last column of Table I. Subsequent calculations indicated that the corrections used for the last four years were not very satisfactory.

The next procedure was to find the direct correlation between the various meteorological elements and the wheat-yield. This was done by taking the monthly values of the meteorological elements and correlating, at first, for each month separately. Some of the results obtained are given in Table II. It was assumed that the yield in each year might be affected by the meteorological conditions obtaining between the beginning of March in the previous year to the end of February in the year in question.

TABLE II. CORRELATIONS WITH WHEAT-YIELDS AT LINCOLN (1).

Month.	Element.			
	Rainfall.	Maximum Temperature.	Minimum Temperature.	Number of Frosts.	Number of Wet and Rain-wet Days at 9 a.m.
January	+.20	-.26	+.09	..	-.06
February	-.00	-.14	+.12	..	-.11
March	-.07	-.08	+.03	..	-.07
April	-.13	+.11	-.20	+.10	+.22
May	-.41	+.07	+.21	+.01	+.00
June	+.31	+.10	-.07	-.05	+.31
July	+.53	-.68	+.25	+.11	+.09
August	-.08	+.30	-.12	+.10	+.11
Sept-Oct	+.47	-.11	+.00	-.11	+.47
October	-.26	+.11	-.23	+.07	-.26
November	+.00	-.00	+.00	-.00	+.00
December	-.00	+.00	-.00	+.00	-.00

From remarks by Dr. Hilgendorf it appeared likely that frosts had an influence on the wheat-yield, especially in certain months. The number of ground frosts (grass minimum thermometer below 30.5° F.) was therefore tabulated for each month and the correlation coefficients calculated as shown in Table II. The hot and dry north-west winds, which are so important a characteristic of the Canterbury Plains, were also thought likely to affect the yield. There were no very satisfactory data regarding these winds, but it was thought that the number of west or north-west winds recorded at 9 a.m. in each month would give a rough measure of the prevalence of north-westerlies. The coefficients shown in the last column of Table II were therefore arrived at. The correlations over a period of twenty-seven years, coefficients as high even as 0.3 are not necessarily significant. Chance distributions may give an occasional coefficient of as high a value. When coefficients are higher, the probabilities of a chance effect are much reduced. The significance of the coefficients in Table II is frequently increased considerably by the fact that consecutive months give similar coefficients, although the relationship between the meteorological elements in successive months is usually slight.

From the results given in Table II, and numbers of others, and after combining months in various ways, certain conclusions were reached regarding the connection between weather and wheat-yield. First, it appears that winter conditions have only a slight influence on the yield, the most important period being from October to February, and especially November to January. Next, any factor leading to increased dryness is favourable to a good yield when it occurs in the winter months and unfavourable when it occurs in the spring and summer months. A special effect is the adverse influence of rainfall in February. This is no doubt due to losses in harvesting caused by the beating-down of the plants and the falling of wheat from the ears. March conditions, as would be expected, appear to have little influence on the crop.

For most elements, therefore, the year was divided into two periods - the winter period, from April to September inclusive, and the summer period, from October to February. In the case of rainfall and rain days, however, for reasons which will be obvious from the foregoing, February was treated separately, and the remainder of the summer months, November, December, and January, were grouped together, since these gave a higher correlation than when combined with October.

The mean values of the different elements for the months mentioned were then correlated with the wheat-yield, and the results which it was considered might be significant are tabulated in Table III. Cloudiness at 9 a.m. gave a fairly high positive correlation for the summer months, but, since the other evidence indicated that sunny weather was favourable to the yield, it was concluded that the effect was spurious and due to some special conditions prevailing at 9 a.m. It is possible that cloudiness in the early morning

is characteristic of certain types of fine weather. The cloud observations, therefore, were not used. Such evidence as there was pointed to sunshine having a beneficial effect at all times of year, and it seems likely that such is the case. The correlations with sunshine, however, are unreliable, for three reasons: (1) the record covers twenty years only; (2) there are a number of breaks; and (3), most important, there has been a continual decrease in the amount of sunshine recorded owing to the growth of trees round the Meteorological Station. The amount of sunshine recorded in recent years is not more than two-thirds that of early years. The progressive change was itself sufficient to cause an apparent correlation over the period of the record. Sunshine was therefore omitted from the list of elements dealt with. The wind record had been affected in a similar manner to the sunshine, the average force being even more markedly reduced than the amount of sunshine. Wind-force also was omitted from the calculations. It is true that, to some extent, the wheat-fields would experience the same changes as the meteorological station, the general increase in tree-growth in the region reducing the amount of wind and sun felt by the crops. The reduction would, however, be much less in the case of the large wheat-fields than for the meteorological station, which was much more confined.

Now, in order to determine the precise effect of each element by itself on the wheat-yield it is necessary to eliminate the effects of the mutual relationships of the elements among themselves. For instance, much of the apparent connection between rain days and wheat-yield might be due to the fact that the number of rain days is closely related to the amount of rain. The partial correlation coefficients have therefore to be found. The first step in the computation of the partial coefficients is the determination of the total correlations between each of the quantities concerned. Since these are of interest in themselves, they have been included in Table III. Each figure in the table is the total correlation coefficients between the quantities represented by the letters at the ends of the corresponding row and column. Thus the total correlation between the November to January elements (c) and the November to January rain days (f) is +.80.

TABLE III. - TOTAL CORRELATION COEFFICIENTS.

	a = Lincoln College Wheat yield.	b = Rainfall, April to September.	c = Rainfall, November to January.	d = Rainfall, February.	e = Rain Days, April to September.	f = Rain Days, November to January.	g = Rain Days, February.	h = W. and N.W. Winds, April to September.	i = W. and N.W. Winds, October to February.	j = Temperature Range, April to September.	k = Temperature Range, October to February.	l = Maximum Temperature, April to Sept.	m = Maximum Temperature, October to February.	n = Minimum Temperature, April to September.	o = Minimum Temperature, October to February.	p = Number of Frosts, April to September.	q = Number of Frosts, October to February.
b	-.17																
c	-.59	+.02															
d	-.50	+.07	-.07														
e	-.18	+.70	+.12	+.05													
f	+.83	-.07	+.80	+.19	-.02												
g	-.27	+.02	.00	+.57	-.04	+.11											
h	+.28	-.42	+.01	-.07	-.29	-.05	+.14										
i	-.51	-.05	-.37	+.25	-.13	-.16	+.44	-.14									
j	+.15	-.76	-.17	-.16	-.72	-.02	-.44	+.42	+.04								
k	-.51	-.15	-.61	+.05	-.19	-.39	+.13	-.17	+.51	+.12							
l	-.12	-.63	+.06	+.21	+.53	+.03	+.06	+.18	+.03	+.53	+.24						
m	-.30	-.22	-.59	-.07	-.22	-.60	-.08	-.14	+.35	+.13	+.74	+.21					
n	-.14	+.02	+.22	+.24	+.09	+.02	-.20	-.11	+.11	-.29	-.13	+.53	+.13				
o	+.19	-.12	-.07	-.37	-.07	-.20	-.25	-.03	-.12	+.06	+.33	+.01	+.49	+.31			
p	+.14	-.16	+.22	-.14	+.07	+.30	+.10	-.31	+.05	.00	-.16	-.21	-.13	-.21	+.04		
q	-.10	-.35	-.13	+.08	-.11	+.05	-.16	+.03	+.13	+.22	+.06	+.10	-.07	-.08	-.17	+.58	+1.00

A very interesting feature of the table is the smallness of the correlation between the various meteorological elements. The correlation between the November to January rainfall and both the April to September rainfall and the February rainfall, for instance, is negligible, and the same is true of the rain days. Rain days and rain are closely related if the means for a number of months be taken, but the value +0.57 is surprisingly low for the correlation between rain and rain days in February. Among the relationships to be deduced from the table the following may be mentioned: Rainfall is likely to be less than normal when north-westerlies are prevalent. Frosts are slightly less frequent in rainy seasons. The temperature range, or difference between maximum and minimum for each day, is reduced by rainfall, the correlation being fairly high. This is chiefly due to the effect of rainfall in decreasing the maximum. The maximum would rise highest on clear, dry days. The prevalence of north-west winds in summer appears to be slightly favourable to increased rainfall in February. This is probably a true relationship, rainfall being light in February, when the general movement of the air from the westward is less pronounced than usual and conditions tend to stagnate. The correlation between west and north-west winds in winter and summer respectively is slight but negative. This also is quite probably real. If the westerly circulation is pronounced in autumn and winter, the reverse is likely to be the case in spring and summer. The temperature range is high when north-westers are frequent, mainly owing to high maxima. The temperature range depends more on the maximum than on the minimum temperature. On the whole, maximum and minimum vary together. If the winter has been frosty, spring and early summer are likely to be also.

Now, the accurate computation of partial correlation coefficients with the wheat-yield for all the elements listed in Table III and from the data given therein would be a very laborious process. Certain approximations had therefore to be made. In the first place, it was assumed that the effects of the elements designated by l, m, n, o, p, and q respectively in Table III could be neglected in a first approximation. Next, it was considered that c, d, f, g, i, and k, which refer to spring and summer months, could be considered independent of b, e, h and j, which refer to winter months. Some of the other quantities also are practically independent of one another. In this way the computation was reduced to manageable proportions, and approximate partial coefficients for c, d, e, f, g, h, i, j, and k with regard to each other were computed. From these, the regression equation -

$$a = .00b + .13c - .54d - .15e + .50f + .20g - .08h - .12i + .27j - .34k$$

was deduced.

The wheat-yield was computed from this formula, and the result gave a correlation of +0.86 with the actual figures as given in the last column of Table I. And whereas the standard deviation of the wheat-yield was 8.4 bushels per acre, the standard deviations of the residuals, or the difference between the actual and the computed yields, was only 4.4 bushels per acre.

The residuals were next correlated with l, m, n, o, p, and q. The correlations with l, p, and q were negligible: that is, the maximum temperature in winter and the number of frosts have no appreciable influence on the yield. The maximum temperature in summer was found to have a considerable effect, and in the opposite direction to that indicated by the total coefficient. The negative total coefficient is due to the correlation of the maximum temperature with rainfall and rain days and temperature range. When the influences of these factors are removed the positive relation between wheat-yield and summer maximum temperatures appears. n gives a slight negative correlation with the residuals, and o a rather larger positive correlation. Temperature, therefore, appears to have little influence in the winter period, but warmth is beneficial in the summer period.

The regression equation finally arrived at, then, was -

$$a = + .13c - .54d - .15e + .50f + .20g - .08h - .12i + .27j - .34k + .47m - .10n + .25o$$

In this equation, however, in addition to other approximations, the mutual influences of the new factors and the earlier ones have not been entirely removed. This refers especially to m, c, f, and k. The coefficient of m should probably be higher and those of c, f, and k lower than those given. The equation gives a correlation of +0.88 with the actual wheat-yield, and the standard deviation of the residuals is reduced to 3.8 bushels. The computed and the actual yields are compared in figure 1. The agreement is rather better than was hoped for when the investigation was commenced. The most serious difference occurs in 1910, when the error in the computed yield is 10 bushels per acre. In 1925 it is 7 bushels, and in 1912 and 1913 6 bushels per acre. The most important factors are November to January rain days, February rain, and summer maximum temperatures.

It must be remembered that the equation represents only mathematical relationships between the figures dealt with. It is not safe to conclude that they represent physical relationships. Again, as was indicated earlier, a high accuracy cannot be expected from the data, so that some of the smaller coefficients especially may not be reliable. Another point, and this must be strongly emphasized, is that the results apply only to Lincoln College. The wheat-growing areas in Canterbury have, in general, a higher rainfall than Lincoln. On the other hand, the Canterbury Plains are saturated with artesian water, and the water-table, especially in winter, is never far below the surface in Lincoln. Conditions at Lincoln are therefore not necessarily representative of the wheat areas of Canterbury.

The tentative conclusions that I would draw from the final results are -

1. The weather variations in winter are responsible for only very slight variations in the wheat-yield. Cool and dry conditions are probably favourable.

2. In spring and summer warm and moist conditions are favourable, especially in the growing-period, but considerable losses may be caused by heavy rain in February.

3. There seems to be little prospect of making a useful crop forecast any considerable time before harvest, since conditions in the period immediately preceding the cutting of the crop have the greatest influence on the yield.